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SUMMARY

Axial fatigue tests at zero mean stress have been made on 0.032- and 0.064-inch 24S-T and 0.032-inch 75S-T sheet-metal specimens 1/4, 1/2, 1, and 2 inches wide without a hole and with central holes giving a range of hole diameter d to specimen width w from 0.01 to 0.95. No systematic difference was noted between the results for the 0.032-inch and the 0.064-inch specimens although the latter seemed the more consistent. In general the fatigue strength based on the minimum section dropped sharply as the ratio d/w was increased from zero to about 0.25. The plain specimens showed quite a pronounced decrease in fatigue strength with increasing width. The holed specimens showed only slight and rather inconclusive evidence of this size effect. The fatigue stress-concentration factor was higher for 75S-T than for 24S-T alloy. Evidence was found that a very small hole would not cause any reduction in fatigue strength.

INTRODUCTION

Axial fatigue tests of strips with circular holes were made at the National Bureau of Standards under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics in order to study the effect of stress concentration on the axial fatigue strength of 24S-T and 75S-T aluminum-alloy sheet.

Specimens with circular holes were selected for this study for the following reasons. They present a stress concentration which is common in aircraft structures. The stress distribution near the hole can be estimated from plane stress theory. The theoretical stress-concentration factor relative to the average stress over the minimum section can be varied from about 3 to 2 by increasing the ratio of hole diameter to width of strip from a value small compared with 1 to a value approaching 1. The dimensions of the region subjected to high stress can be increased in proportion to the size of the hole. Fatigue tests of strips with or without holes can be made by means of a technique already developed.

APPARATUS AND SPECIMENS

Two machines, machine a shown in figure 1 and machine b shown in figure 2, were used. These have been described in detail in reference 1. Machine a consists of a lever mounted on crossed flexure plates at the fulcrum. One end of the lever is driven by an adjustable crank; the specimen is gripped between the other end and the frame of the machine. The speed is 1000 cycles per minute.

Machine b was adapted from a design of the Aluminum Company of America. The load is applied to the specimen by means of a Scotch yoke driven by an adjustable eccentric. A dynamometer loop is in series with the specimen. Four specimens may be tested simultaneously. The speed is 2000 cycles per minute.

The capacity of both machines is ±1500 pounds. Both machines are equipped with limit switches and relays which disconnect the motor when the specimen fails. Both machines are essentially of the "constant-load" type because of the flexure of the lever of machine a and the deflection of the elastic loops of machine b. Any change in the deformation of the specimen would be small compared to the stroke of the crank divided by the lever ratio in the case of machine a and to the stroke of the eccentric in the case of machine b.

It was necessary to apply a correction ranging from 3.5 to 8.0 percent to the static-load setting of machine a for the "dynamic overthrow" due to the inertia of the lever. The amount of the correction was determined by means of Tuckerman optical strain gages, as described in reference 2. Sufficient specimens were tested for overthrow so that the amount of overthrow could be obtained to the nearest 0.5 percent for any specimen either directly or by interpolation.

Guide fixtures were used on all specimens to prevent buckling during the compression half of the cycle. In principle these were exactly the same as those described in reference 2 but several guides were used, the type depending on the size of the specimen. Each consisted of a pair of stiff lubricated members held against the faces of the specimen by side plates. It is shown in reference 2 that the friction of the guides had a negligible effect on the strain amplitude for specimens 0.032 inch thick by 0.5 inch wide. Further tests were made in the present investigation on specimens 0.064 inch thick by 2 inches wide with a 1.9-inch central hole. It was believed that the effect of friction of the guides would be the greatest in this specimen. Tuckerman optical strain gages having a 1-inch gage length and equipped with special rigid knife edges for use in fatigue tests were mounted on the edges of the specimen at the hole, as shown in figure 4 of reference 2. With the guides off, the strain amplitude per unit of load was obtained for tensile load. With the guides on, the strain amplitude was determined under completely reversing load of an amplitude about equal to the minimum used in obtaining the S-N curve for this specimen. When the guides were normally tight the same strain amplitude per unit of load was obtained as for tensile loading with the guides off. It was found possible by overtightening the guides to produce sufficient friction to reduce the strain amplitude by 6 percent in this specimen.

The tests in machine a to determine dynamic overthrow and friction provided an opportunity to observe the equality of the strain amplitude on both edges of the specimen. In almost every case the strain amplitude at one edge was found to agree with the amplitude at the other edge to within the error of reading the Tuckerman gages under dynamic conditions. With a dumbbell reticule the strain could be read to one-half a scale division or 0.00002 inch per inch.

It was found impracticable to use optical strain gages in machine b because of the great acceleration and the horizontal position of the specimen.

A plan view of the specimens is shown in figure 3. Most 24S-T specimens were made in both 0.032-inch and 0.064-inch sheet; the 75S-T specimens were made in 0.032-inch sheet only. The upper specimens in figure 3 were tested in machine a. The lower, which were wider at the grips than machine a could accommodate, were tested in machine b. There was no evidence of a systematic difference between results obtained in the two machines which could be attributed to differences in the machines rather than to differences in the specimens. The specimens which had no hole are termed "plain" specimens. The same type number is used to designate both plain and holed specimens.

Tests were made on specimens of the material to determine static yield strength, tensile strength, and elongation. The compressive yield strength was determined on rectangular strips 0.50 inch wide and 2.25 inches long restrained against buckling by lubricated steel guides, as described in reference 3. The results are given in table 1.

The widths of the fatigue specimens were 1/4 inch, 1/2 inch, 1 inch, and 2 inches. In general for each width w the hole diameter d was made equal to $w/4$, $w/2$, and $3w/4$, but additional 24S-T specimens were included for $w = 1/4$ inch and $w = 2$ inches with a 0.02-inch hole and $w = 2$ inches with a 1.9-inch hole. Also 75S-T specimens 2 inches wide with a 0.02-inch hole were included. It was necessary to omit several combinations of d and w because of capacity limitations of the machines. The combinations which were included are given in table 2.

The reduced-section specimens were machined in stacks by the method described in reference 1. The slight taper of the reduced section from the ends toward the middle was necessary in the case of the plain specimens to avoid failure at the shoulders. It was convenient to machine the holed specimens in the same fixture - thus they also are tapered; w refers to the width at the hole. The longitudinal edges of the rectangular specimens, type III, were machined in a shaper. A light depth and feed were used for the finishing cut.

All holes greater than 1/4 inch in diameter and some 3/16 and 1/4 inch in diameter were finished by boring. The specimen was centered on the faceplate of a precision lathe by means of a micrometer dial indicator. The deviation of the center of the hole from the longitudinal center line of the bored specimens usually did not exceed 0.0005 inch but may have been as much as 0.001 inch in some cases. The depth of the finishing cut was approximately 0.001 inch and the feed was 0.001 inch per revolution. The slight burr that remained at the rim of the hole was not removed as it was not desired to chamfer the rim of the hole and it would be difficult to deburr all the holes in a uniform manner.

Some $\frac{3}{16}$- and $\frac{1}{4}$-inch holes were reamed. The $\frac{1}{16}$-inch holes were reamed by means of a size AAA die-maker's reamer, which tapers 0.013 inch per inch. Some $\frac{1}{8}$-inch holes were reamed; some were drilled. The S-N curve for the 0.032-inch 24S-T specimens with a 0.1285-inch (nominally $\frac{1}{8}$-inch) hole was taken from reference 1. Tests seemed to indicate that there was no difference in the fatigue strength for the $\frac{1}{8}$-inch drilled and reamed holes in specimens 1/2 inch wide. The 0.020-inch holes were drilled.

TESTS

S-N data were obtained on a series of specimens for each combination of thickness t, width w, and hole diameter d and covered a range of values of N from about 10^4 to a few million. (N is the number of cycles to failure.) In some cases the loads would have exceeded the capacity of the machine and it was necessary to omit part of this range.

Failure occurred at the hole and progressed from the inside outward at the minimum cross section. The limit switches were set to stop the machine between the time that the load decreased by a few percent and complete failure. It was observed that, after fatigue cracks had progressed to the point where the tensile load was reduced appreciably, further progress to the point of failure was very rapid; hence it was deemed unnecessary to correct N for the small number of cycles immediately preceding failure during which the tensile load had fallen off appreciably.

RESULTS AND DISCUSSION

The S-N curves are given in figures 4, 5, 6, and 7. The stress S was computed by dividing the maximum load by the product of the thickness and the net width at the minimum section; the diameter of the hole was subtracted from the gross width of the holed specimens to obtain the net width. Difficulty was encountered in testing 0.032-inch, 2-inch-wide, plain specimens. Many failed at the grips and the results are not plotted. The results for the others, which had a satisfactory failure, showed considerable scatter. The fatigue strength for failure at three specific values of N is shown in figures 8 and 9. The fatigue strength for the plain specimens is shown at $d/w = 0$. In a few cases the S-N curve was extrapolated slightly to obtain a value of S corresponding to $N = 10^7$ cycles. That portion of the curves in figure 8 determined by extrapolated points is shown dashed. The fatigue stress-concentration factor k_f, which is the ratio of the fatigue strength of a plain specimen to the strength of a holed specimen of the same width, is shown in figures 10 and 11 for $N = 2 \times 10^6$ cycles. The theoretical stress-concentration factor k_t, taken from references 4 and 5, is also indicated.

The S-N curves for the plain specimens (figs. 4 and 7) show evidence of a size effect in that the strength generally decreases as the width increases. This effect is not pronounced in the holed specimens. There is a suggestion that it is present in the results for the 24S-T holed specimens but not for the 75S-T specimens. In both cases it is masked to some extent by the scatter, which was larger for the 24S-T specimens (fig. 8) than for the 75S-T specimens (fig. 9) and decreased as N increased for the latter.

An explanation of the difference in the effect of width of the specimen upon the fatigue strength of plain and holed specimens may lie in the difference in the type of stress-raiser causing failure. Plain specimens fail at a defect such as a nick, scratch, or inclusion of some kind which presumably is randomly located in the specimen. As pointed out in reference 6, the larger the specimen the greater is the probability of the presence of a fatigue nucleus. This is also true to some extent in the holed specimens; however, the volume of metal which is subjected to the stress peak is quite small even in the wider specimens. The probability of the location of a randomly occurring defect within this volume may be slight; the hole is then the controlling stress-raiser and the strength would depend principally on the ratio d/w and on the material.

The holed specimens showed a sudden drop in fatigue strength as the ratio d/w was increased from zero. The fatigue strength of the 75S-T specimens leveled off at approximately $d/w = 0.25$, but the 24S-T specimens showed a slight increase for greater values of the ratio.

The fatigue stress-concentration factor k_f (figs. 10 and 11) showed no definite relation to the width except that k_f for the 0.064-inch 24S-T specimens increased with increasing width. Unfortunately the capacity of the machines did not permit determining k_f for 0.064-inch specimens 2 inches wide. The factor k_f was appreciably greater for 75S-T than for 24S-T specimens but considerably less than k_t. Apparently k_f approaches unity as d is reduced to zero, although the value of k_t computed for an isotropic elastic solid is 3 at $d = 0$. Petersen (reference 7) and others have also noted that k_f tends to approach unity as the size of the stress-raiser approaches zero. It has been suggested that this discrepancy is due in part to the finite size of the crystals; the difference between k_f and k_t would become greater as the size of the hole approached that of the crystal. Obviously this effect is confirmed by practical experience as there are microscopic scratches and discontinuities in even the smoothest plain specimens; these are so small as to be scarcely recognized as stress-raisers but nevertheless have a finite value of k_t.

CONCLUDING REMARKS

Axial fatigue tests at zero mean stress have been made on 0.032- and 0.064-inch 24S-T and 0.032-inch 75S-T sheet-metal specimens 1/4, 1/2, 1, and 2 inches wide without a hole and with central holes giving a range of hole diameter d to specimen width w from 0.01 to 0.95. There seems to be a definite size effect for plain specimens - the narrower the specimen the greater the strength. The holed specimens showed only slight and rather inconclusive evidence of this effect. There was no systematic difference between the fatigue strength of plain or holed specimens 0.032 and 0.064 inch thick. The fatigue stress-concentration factor was higher for 75S-T specimens than for 24S-T specimens. Apparently this factor approaches unity as the hole diameter is reduced to zero.

National Bureau of Standards
Washington, D. C., January 27, 1947

REFERENCES

1. Brueggeman, W. C., Mayer, M., Jr., and Smith, W. H.: Axial Fatigue Tests at Zero Mean Stress of 24S-T Aluminum-Alloy Sheet with and without a Circular Hole. NACA TN No. 955, 1944.

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4. Howland, R. C. J.: On the Stresses in the Neighborhood of a Circular Hole in a Strip under Tension. Phil. Trans. Roy. Soc. (London), ser. A, vol. 229, 1930, p. 49.

5. Wahl, A. M., and Beeuwkes, R., Jr.: Stress Concentration Produced by Holes and Notches. Trans. A.S.M.E., vol. 56, no. 8, Aug. 1934, pp. 617-625.

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7. Petersen, R. E.: Stress-Concentration Phenomena in Fatigue of Metals. Appl. Mech., vol. 1, no. 4, Oct.-Dec. 1933, p. 157.

TABLE 1.- AVERAGE[1] TENSILE AND COMPRESSIVE PROPERTIES OF

ALUMINUM-ALLOY SHEET

Sheet thickness	Longitudinal or transverse	Tensile yield stress[2] (ksi)	Compressive yield stress[2] (ksi)	Tensile strength (ksi)	Elongation in 2 in. (percent)
24S-T sheet					
0.032-in.	Longitudinal	52.4	43.6	71.7	18
Do-----	Transverse	44.9	----	68.2	18
Do-----	Longitudinal	51.0	44.5	72.0	19
Do-----	Transverse	45.8	48.4	69.2	18.5
Do-----	Longitudinal	51.4	44.7	70.9	18
Do-----	Transverse	45.5	47.9	68.4	20
.064-in.	Longitudinal	53.4	43.8	71.2	20
Do-----	Transverse	45.9	49.1	69.4	20
Do-----	Longitudinal	53.9	44.3	71.9	19
Do-----	Transverse	45.4	47.7	69.4	19
75S-T sheet					
0.032-in.	Longitudinal	77.4	74.5	85.0	10
Do-----	Transverse	72.8	79.0	83.3	10.5

[1]The results are the average of from one to four specimens.

[2]0.2-percent-offset method.

TABLE 2.- TYPES OF SPECIMEN (FIG. 3) FOR VARIOUS COMBINATIONS OF ALLOY THICKNESS, WIDTH, AND HOLE DIAMETER

[24S-T specimens 0.032 and 0.064 in. thick and 75S-T specimens 0.032 in. thick were tested in all the combinations of d and w except as indicated]

Hole diameter, d (in.)	Specimen width, w (in.)			
	1/4	1/2	1	2
0	Specimen I	Specimen II	Specimen IV	Specimen VI[1]
.020	Specimen I[2]			Specimen V[1]
1/16	Specimen I			
1/8	Specimen I	Specimen II		
3/16	Specimen I[3]			
1/4		Specimen II	Specimen III	
3/8		Specimen II		
1/2			Specimen III	Specimen V
3/4			Specimen III	
1				Specimen III
$1\frac{1}{2}$				Specimen III
1.9				Specimen III[3]

[1] t = 0.032 in. only.
[2] 24S-T specimens only.
[3] t = 0.064 only.

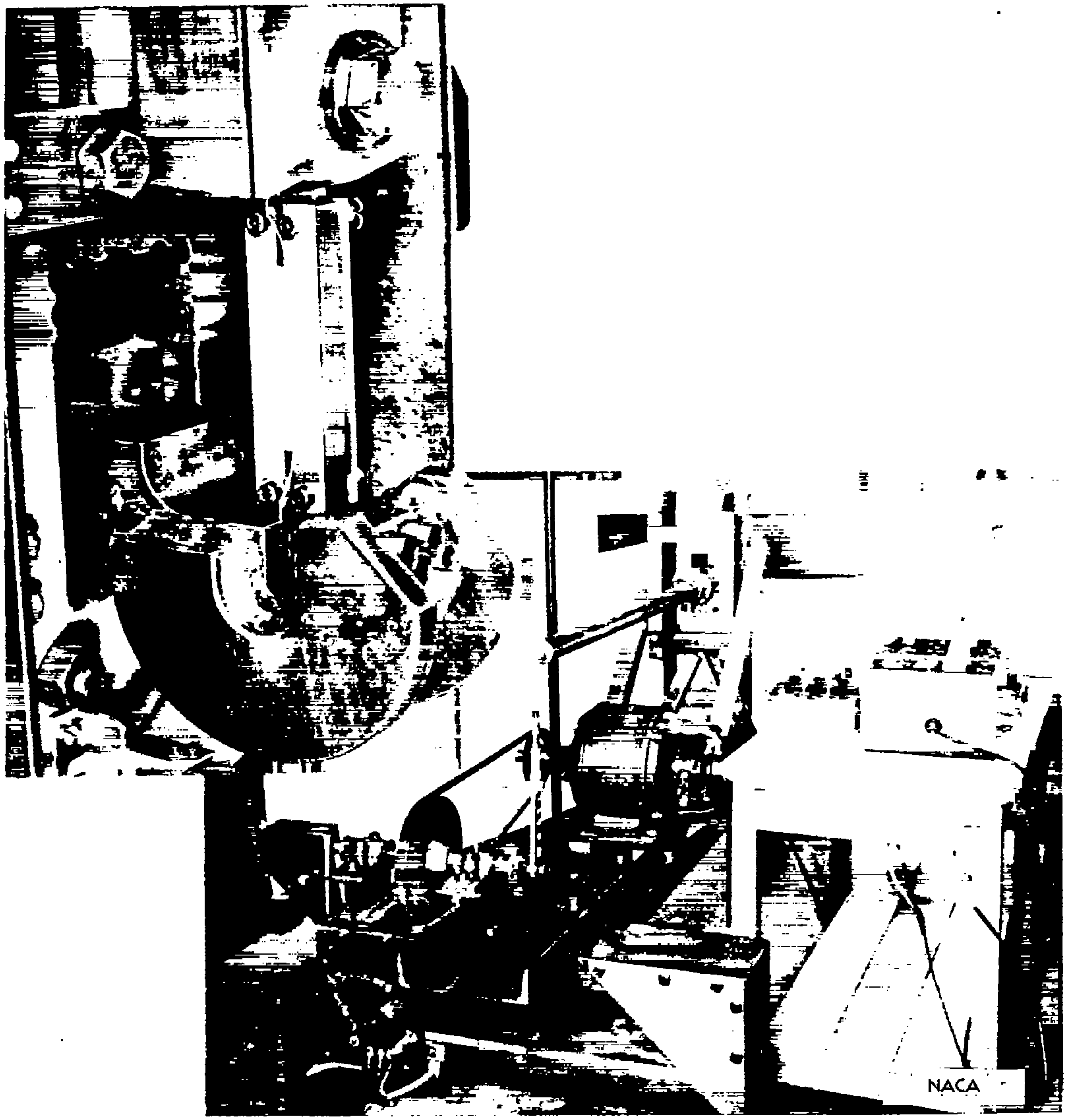

Figure 1.- Fatigue testing machine a.

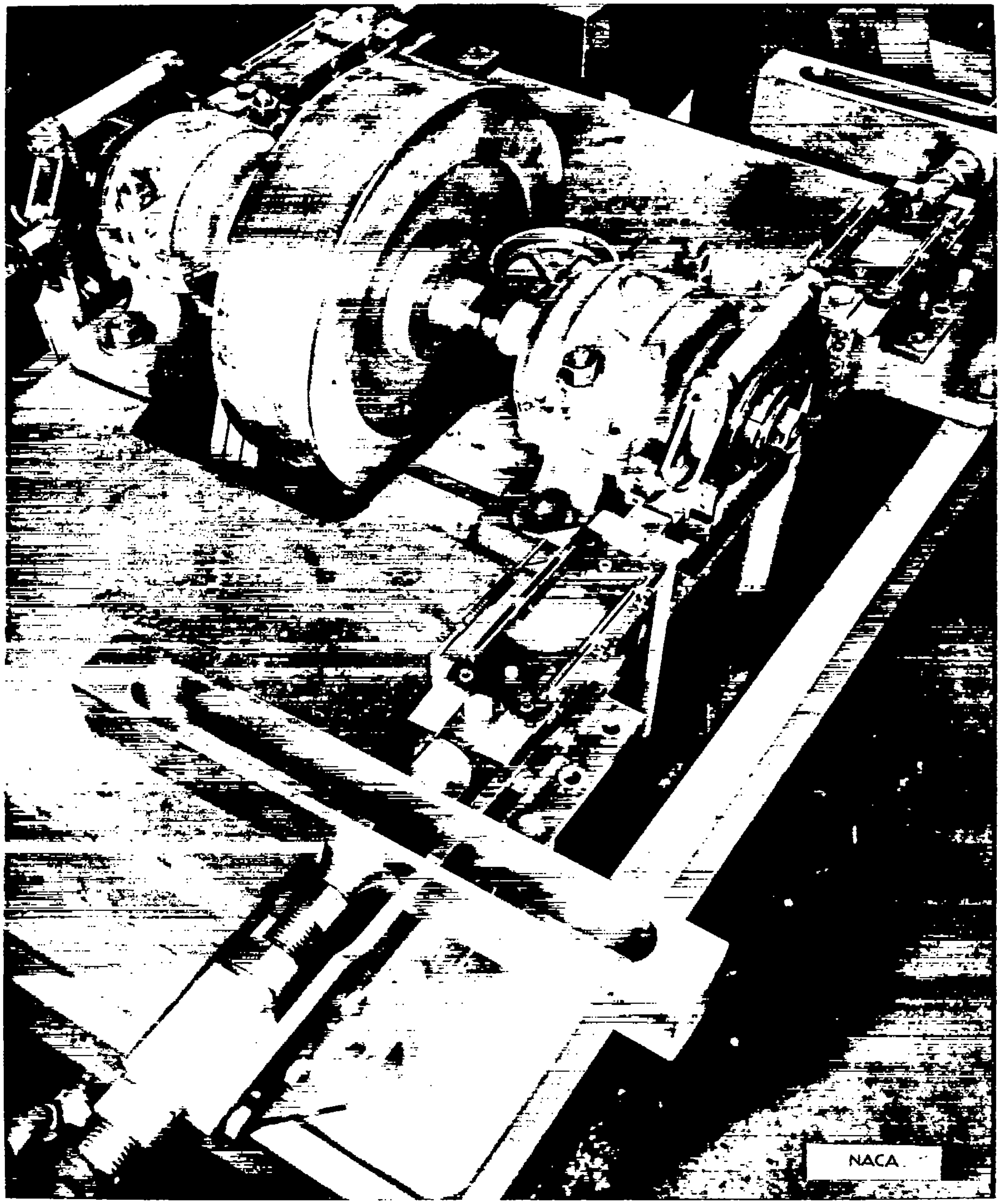

Figure 2.- Fatigue testing machine b.

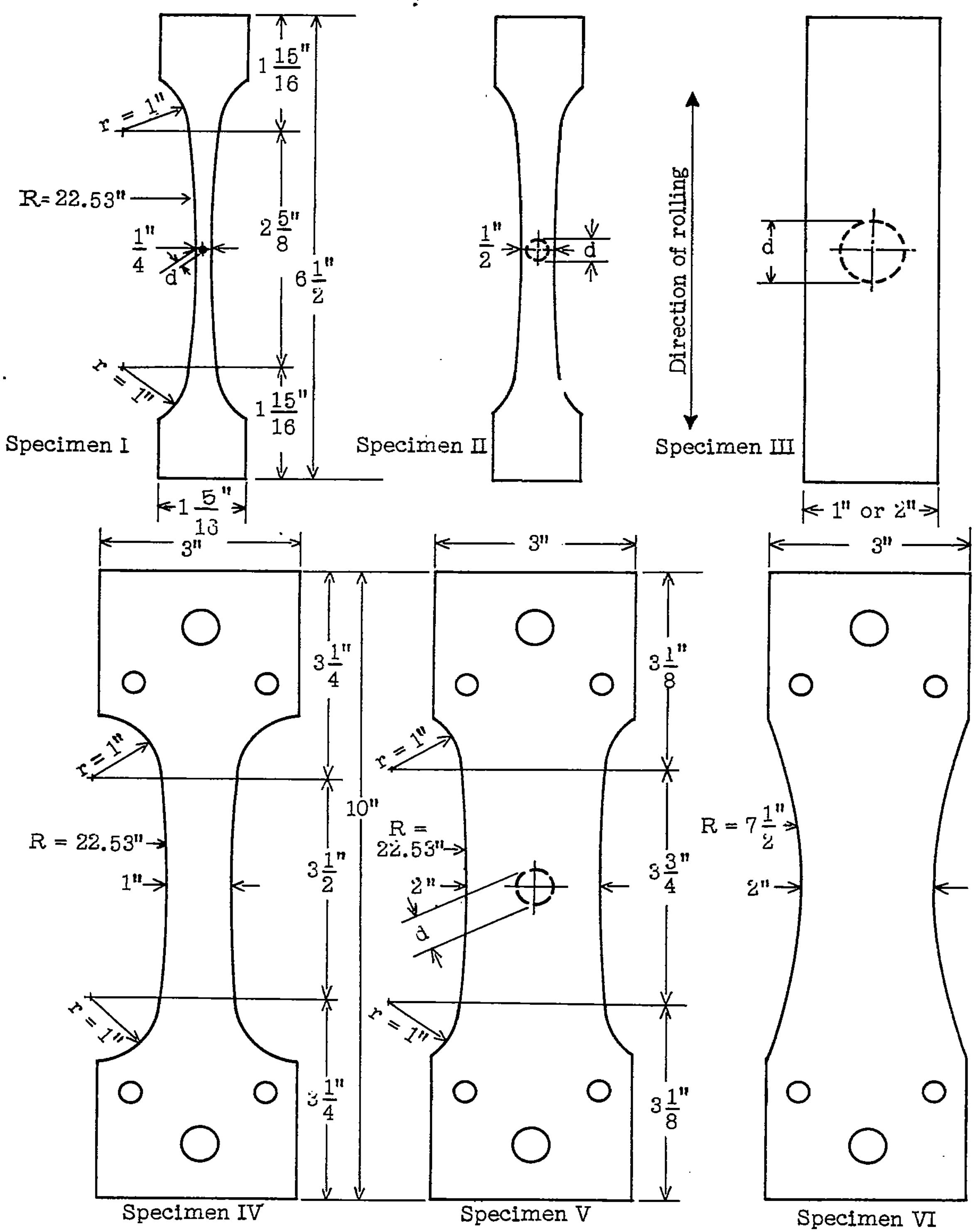

Figure 3.- Fatigue specimens.

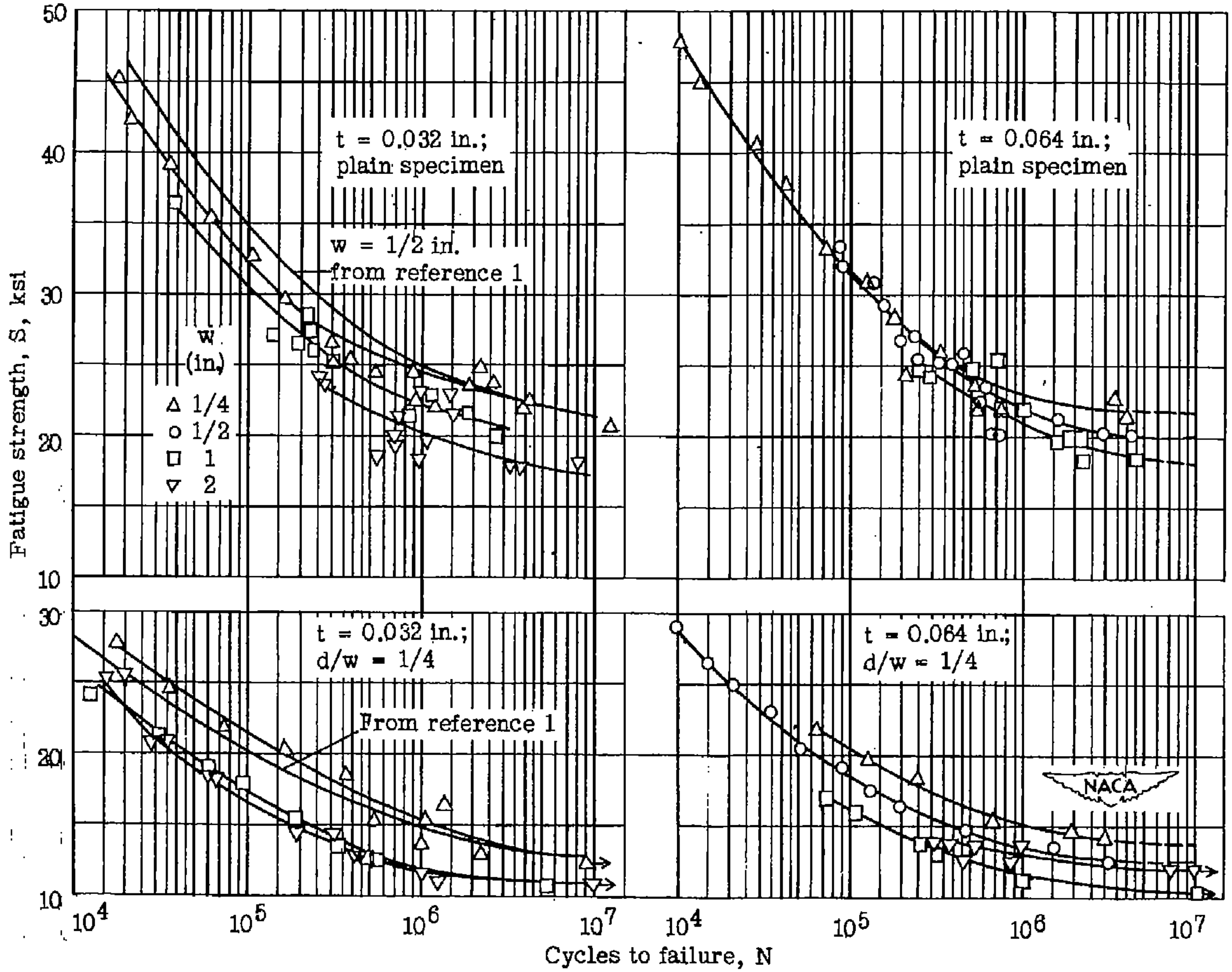

Figure 4.- S-N curves. 24S-T sheet. Plain specimens and specimens having ratio d/w = 1/4.

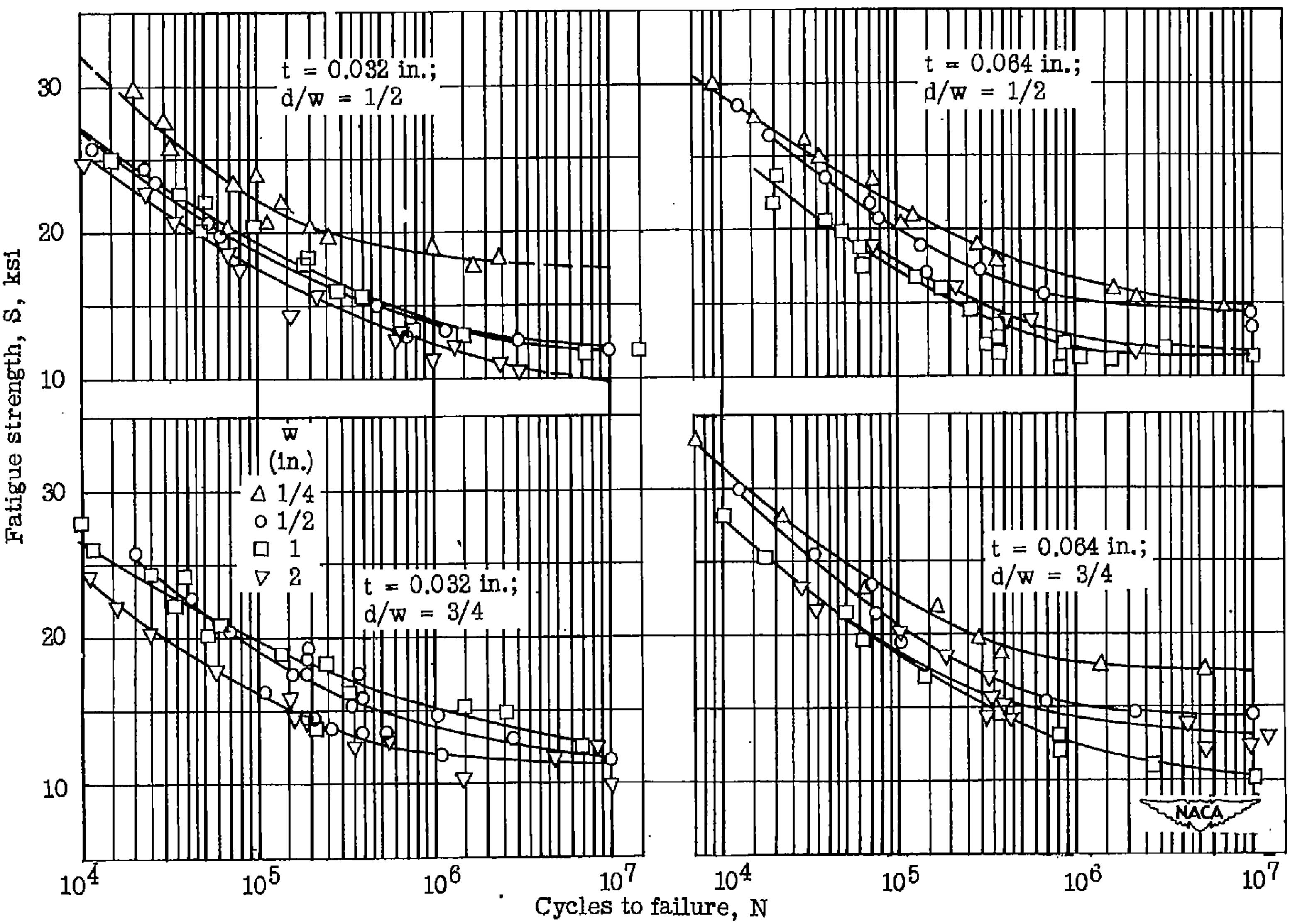

Figure 5.- S-N curves. 24S-T sheet. Specimens having ratio d/w = 1/2 and 3/4.

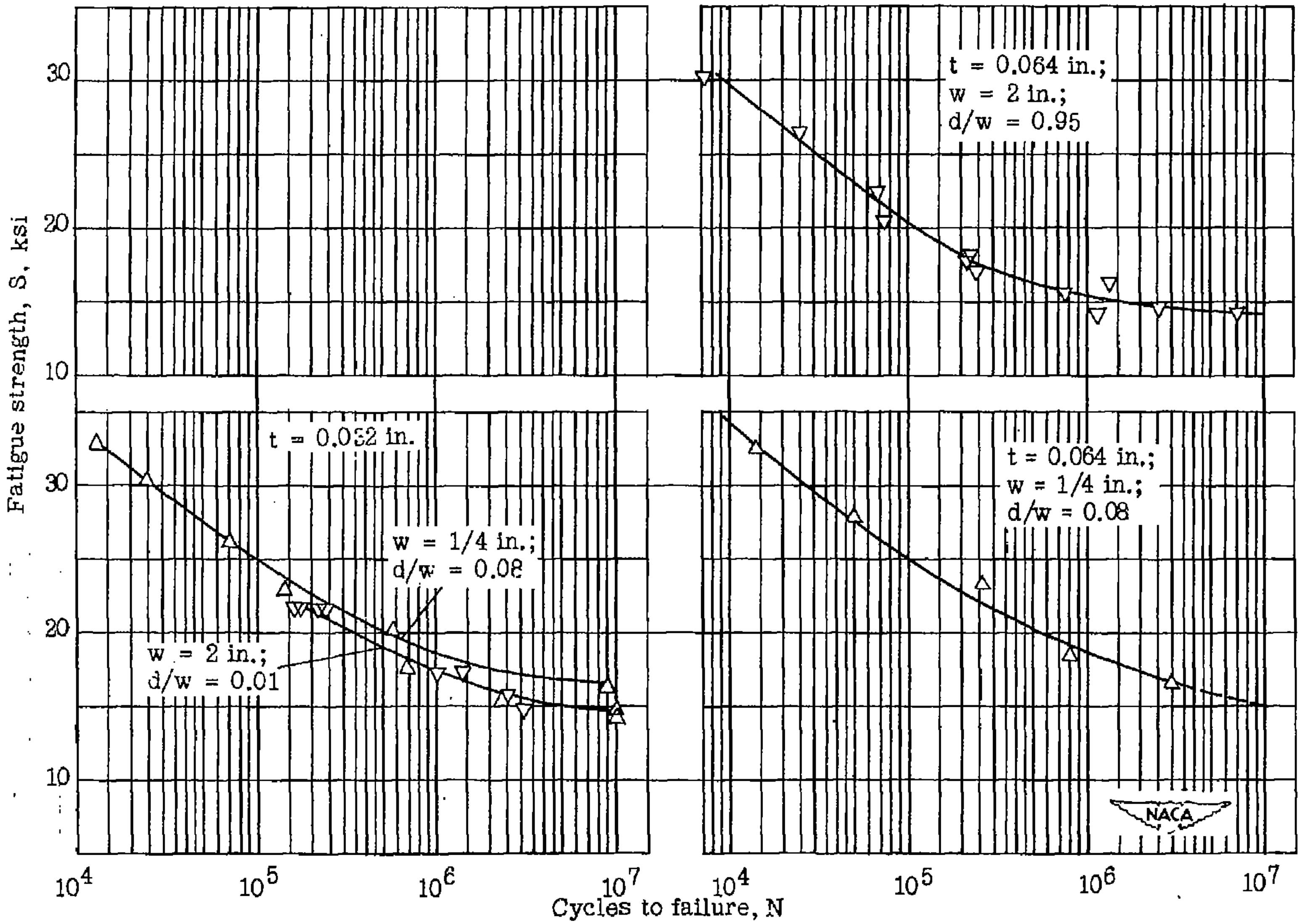

Figure 6.- S-N curves. 24S-T sheet. Specimens having ratio d/w = 0.08 and 0.95.

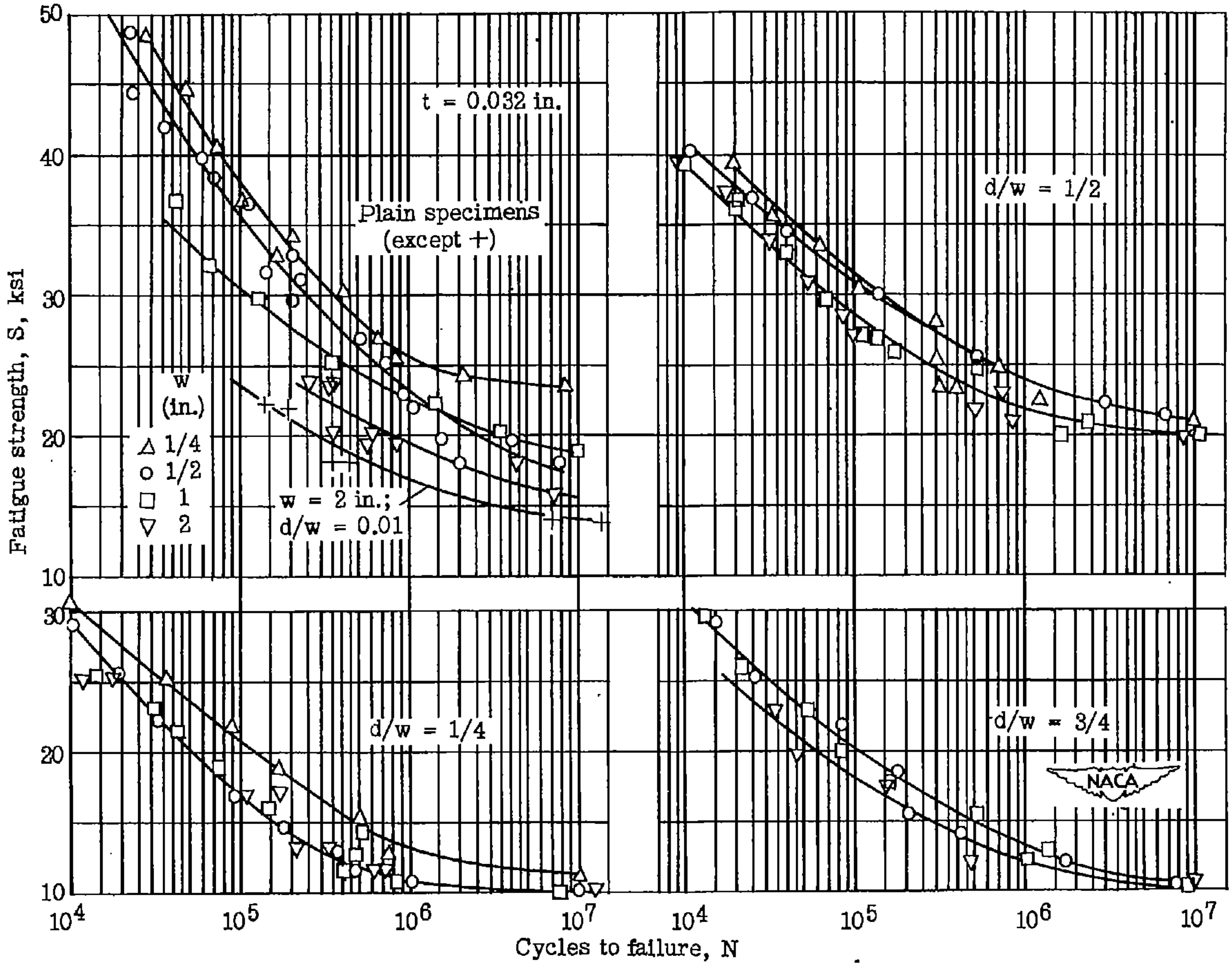

Figure 7.- S-N curves. 75S-T sheet.

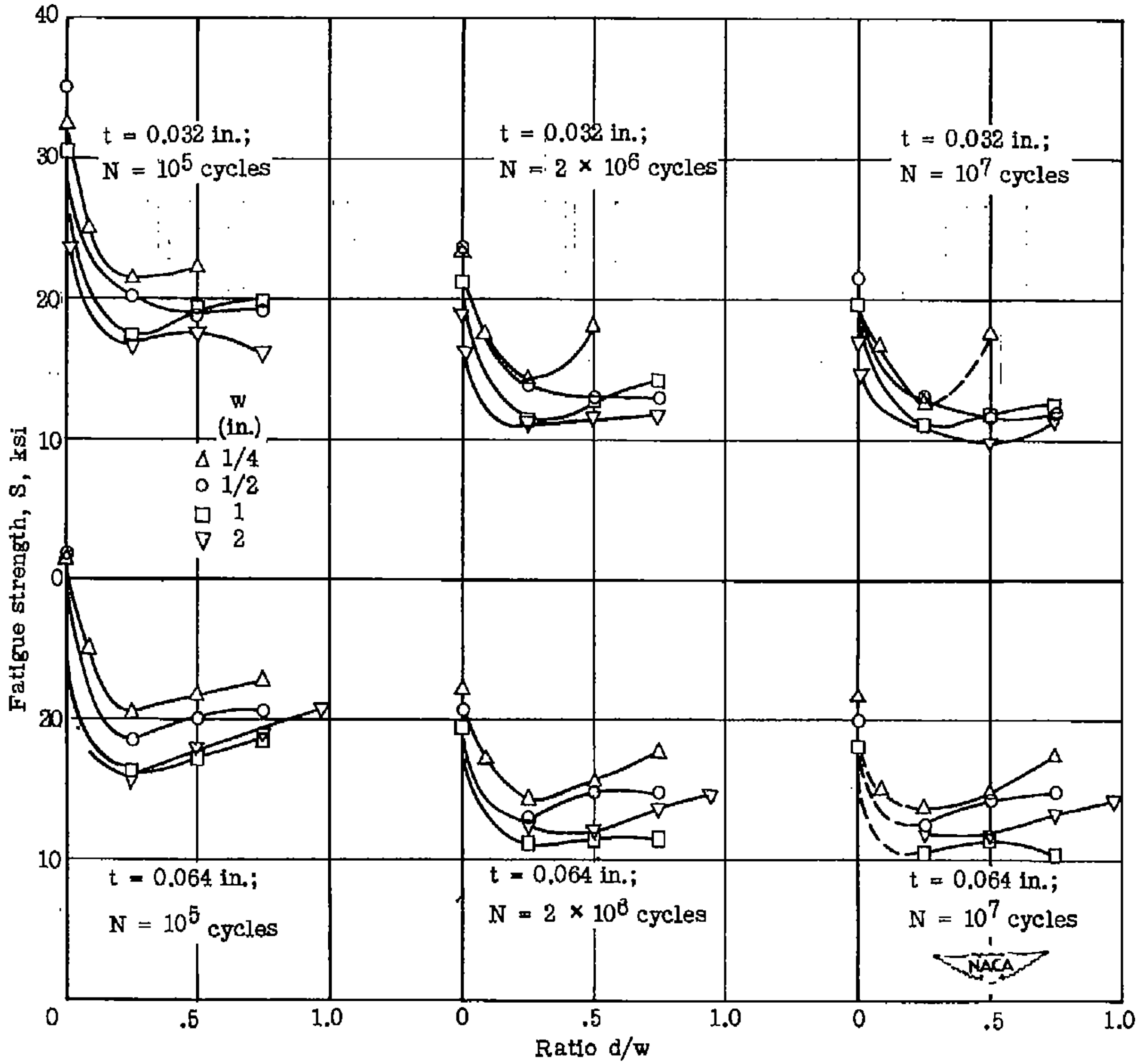

Figure 8.- Fatigue strength for failure at specific values of N. 24S-T sheet.

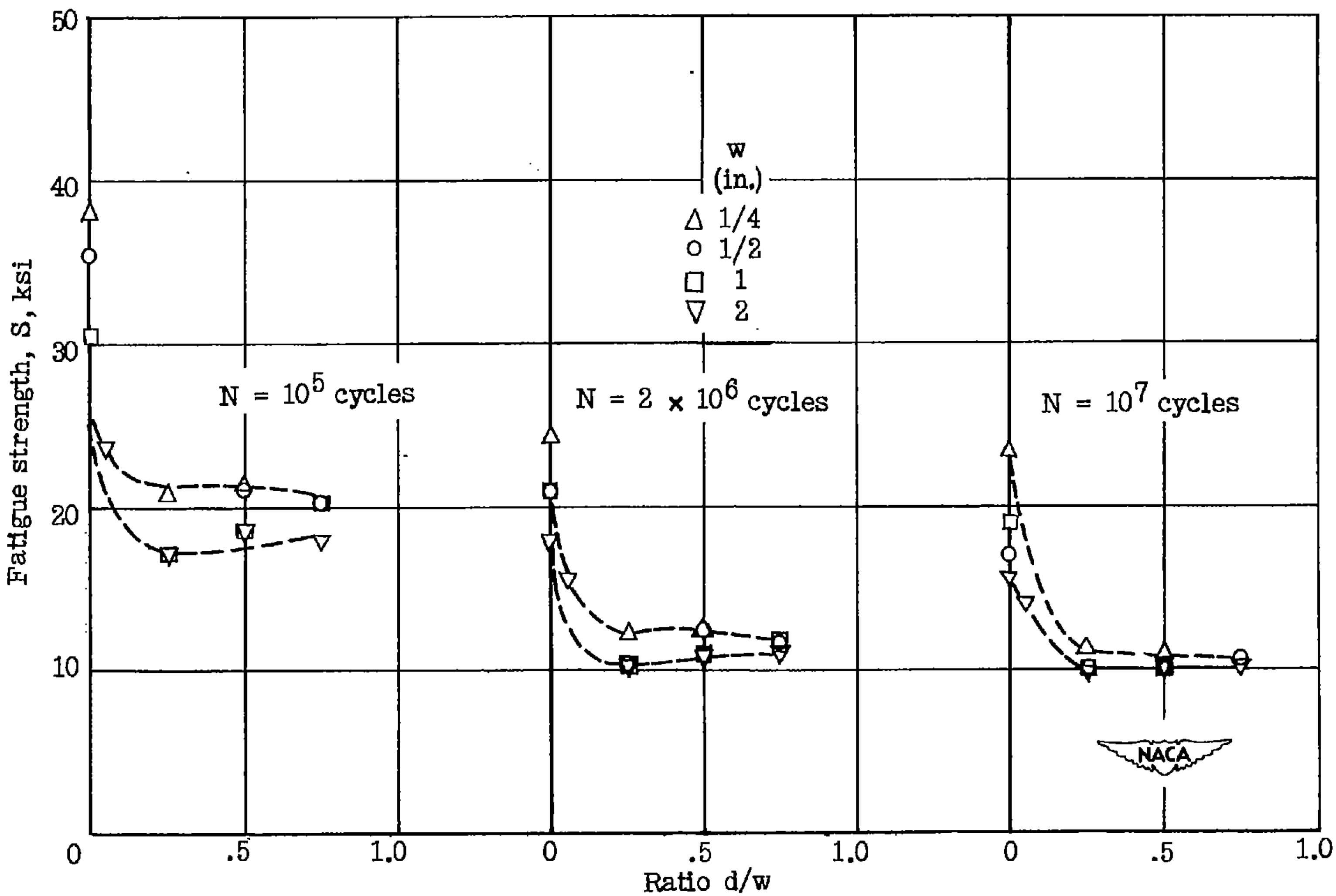

Figure 9.- Fatigue strength for failure at specific values of N. 75S-T sheet; t = 0.032 in. Scatter band for all widths is shown.

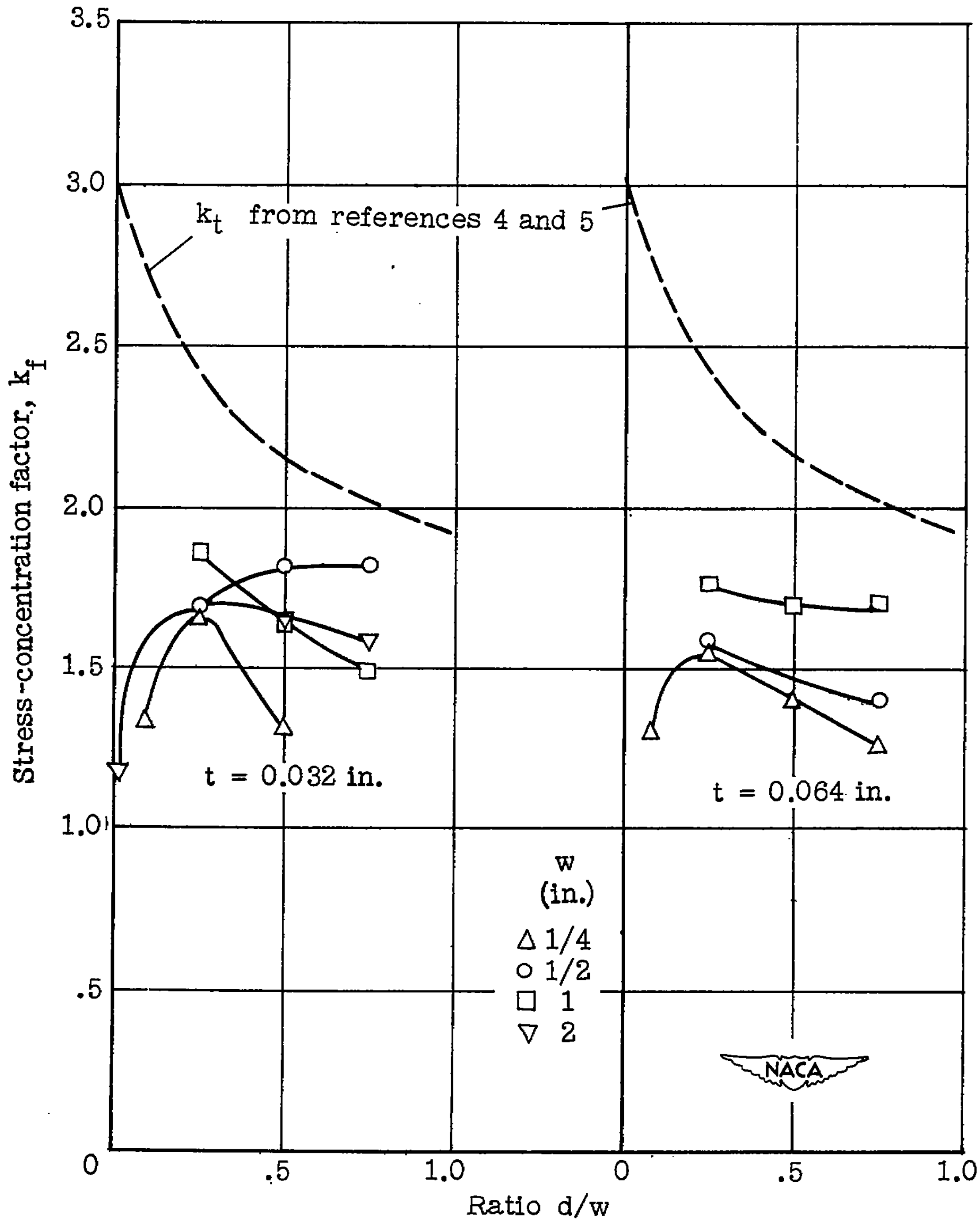

Figure 10.- Fatigue stress-concentration factor k_f at $N = 2 \times 10^6$ cycles. 24S-T sheet.

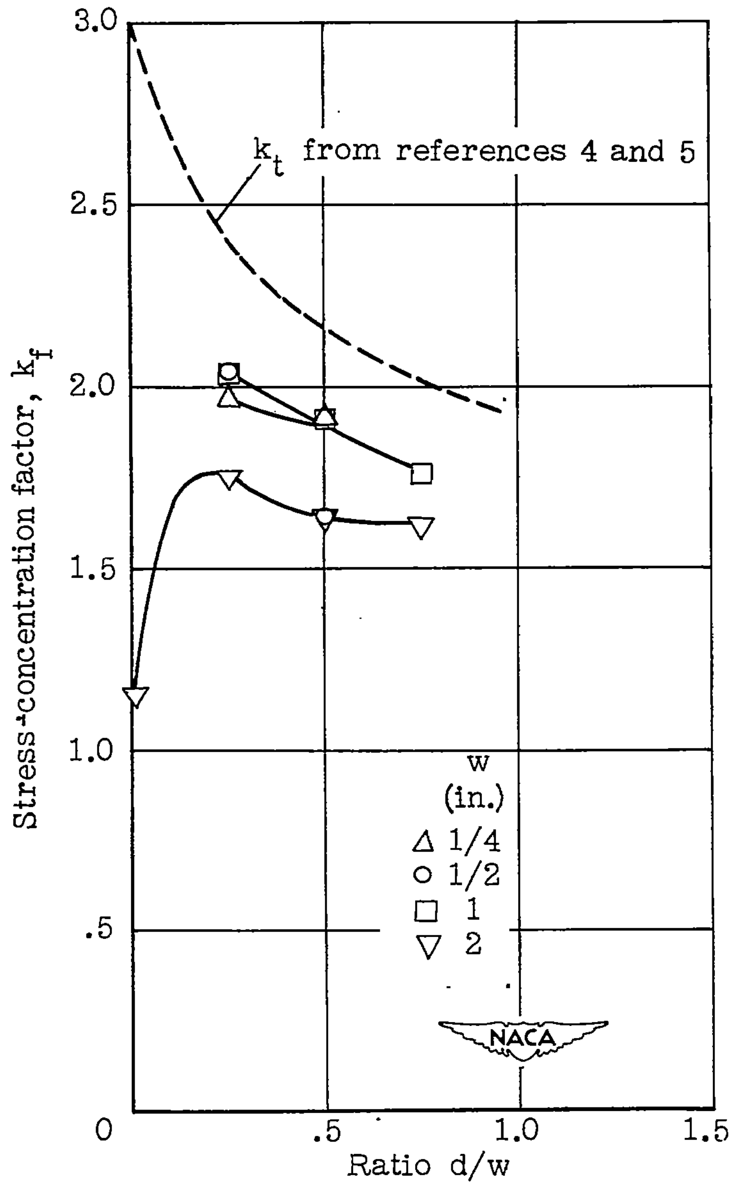

Figure 11.- Fatigue stress-concentration factor k_f at $N = 2 \times 10^6$ cycles. 75S-T sheet; t = 0.032 in.